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A review of high temperature superconductors for offshore wind power synchronous generators

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ABSTRACT

Large synchronous generators with high temperature superconductors are in constant development due to their advantages such as weight and volume reduction and the increased efficiency compared with conventional technologies. The offshore wind turbine market is growing by the day, increasing the capacity and energy production of the wind farms installed and increasing the electrical power for the electrical generators installed, consequently raising the total volume and weight for the electrical generators installed. The HTS synchronous generators (HTSSG) are an alternative to consider due to their low dimensions and low weight per megawatt. This article presents a detailed review of the geometric configurations of the large HTSSG for offshore wind energy followed by an explanation of the main non-conventional technological parts. Additionally, the experience from the most important projects – both ongoing and completed – by companies and research institutes related to the design and construction of HTSSG for offshore wind energy is reviewed.

Contents

Abbreviations: HTS, high temperature superconductor; HTSSG, high temperature superconductor synchronous generator; PMSG, permanent magnet synchronous generators; PMSGDD, permanent magnet synchronous generators Direct Drive; DFIG, doubly fed induction generator; MLI, Multi-Layer Insulation; 1G, first generation; 2G, second generation

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1. Future prospects for offshore wind turbines electrical generators technology

Wind energy is the world's fastest-growing energy. Both in Europe and worldwide, offshore wind power is being developed rapidly due to the stronger and stable winds produced at sea and the huge areas where it can be installed.

Offshore wind power systems have relevant advantages compared with the onshore wind power systems, due to the attractive and easier transport of the components, as well as lower visual impact and noise [1–3].

The wind energy production of recent years has risen and a high and linear evolution of the growth of electrical wind energy is expected as shown in Fig. 1a. Also, a high growth of wind turbines capacity is expected to be installed in the following decade, shown in Fig. 1b.

The average size of offshore wind farm installations in 2012 was 286 MW whereas in 2013 it was 482 MW [5]. Regarding the fleet wind farm size in the EU-12 compared between 2009 and 2013 an increase of the wind turbine power per unit could be observed. By 2009 the average wind power unit was 2.62 MW and by 2013 it had been increased to 3.29 MW [5]. This could be because of the lower operational and maintenance costs required for the overall fleet of the total units.

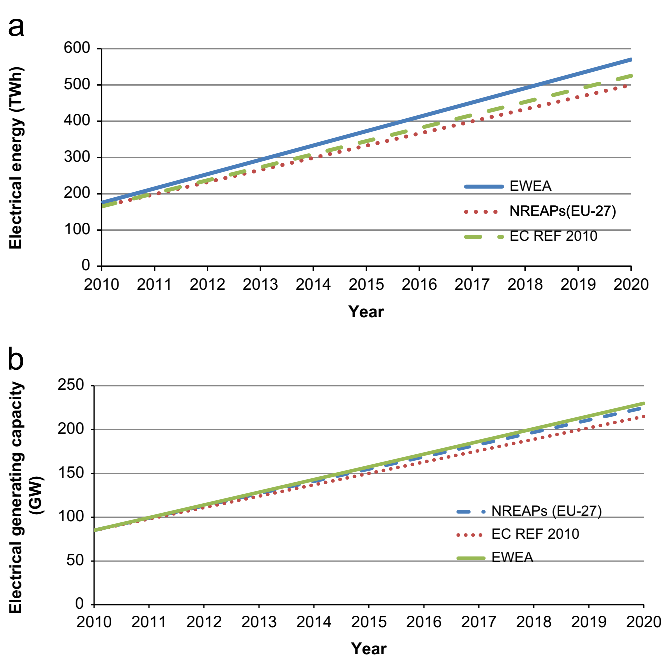

Fig. 1. a) Expected growth in electrical wind energy production (TWh) [4] and b) Expected growth installed in electrical generating wind power capacity [4]

As exhibited in Fig. 2, there is a trend showing an increase in the average wind turbine unit rating every year with the prospects of the higher than 8 MW wind turbine project concept designs and installations for the coming decade.

Table 1 presents the most relevant offshore wind turbines using conventional technologies for more than 4 MW unit rating that have been installed. The wind turbine electrical power, the electrical machine technology used and the gearbox coupled were mainly recorded. As Tables 1–3 indicate, the highest number of offshore wind turbine projects installed and in development for powers more than 4 MW using PMSG exist there, and a significant number of them have a Direct Drive transmission system.

Wind turbines for the offshore market must be extremely reliable and do not need high maintenance. The simplicity and the highest overall efficiency, reliability and low noise for the conventional drive trains without gear boxes for large powers are demonstrated [6–8].

However, for wind turbine electric ratings higher than 8 MW, its geometric dimensions and consequently the total weight of the generator increase exponentially [9]. For this main reason, it is required to search for alternative technologies for offshore wind turbines with powers more than 8 MW to achieve the electrical power with a lower electrical generator volume and a low total weight with reasonable costs.

2. HTSSG for offshore wind energy

High temperature superconductors (HTS) evolve continuously with better electrical, mechanical and magnetic characteristics with a minor cost for application in industrial sectors as wind energy systems.

The result of the high current density in HTS tapes is the high power density obtained in HTS generators. The conventional copper coils in a conventional machine typically operate with a current density between 3 and 5 A/mm^2 while the current density in the wire in a HTS coil can operate at 200 A/mm^2 [10]. As a consequence a higher induction could be obtained by using HTS coils; for this reason it is possible to reduce the main radial and axial dimensions of the electrical generator to obtain the same electrical power. Because of the lower dimensions required a lower weight compared with conventional machines of the same electric rating and nominal speed is needed, proving to be attractive for wind energy.

HTS generators cannot be commercially successful in the wind market without low cost volume production of HTS wire.

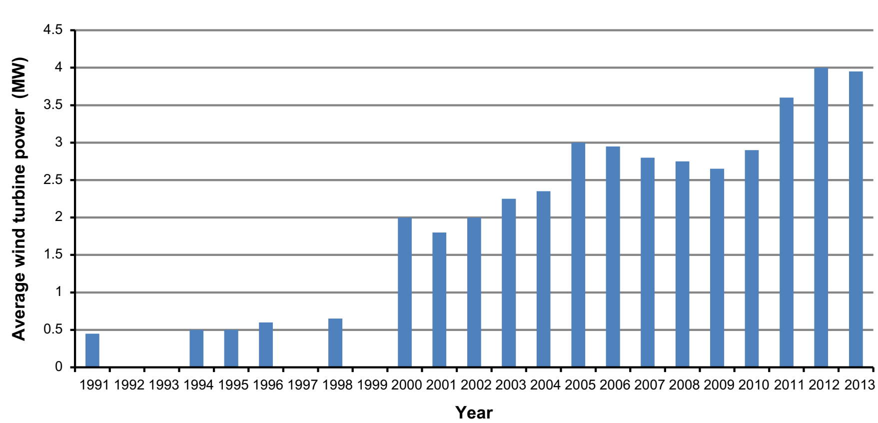

Fig. 2. Annual average sizes of offshore wind turbines in MW [5].

Table 1
Offshore wind turbines installed.

Company	Model	Generator data				Gearbox			Year installed /ref.
		Power (MW)	Tech.	Speed (rpm)	Voltage (V)	Rt	Gears	Type	
Enercon	E-126	7.5	PMSGDD				–	–	2007/[60]
Repower	6M	6	DFIG	750–1170	660		3G		2009/[61]
BARD	BARD 5.0	5.6	DFIG	1212		100	3G		2011/[62]
Repower	5M	5	DFIG	750–1170	660		3G	Planetary/helicoidal	2006/[63]
AREVA Wind Gmbh	M5000-116	5	PMSG	45–148	3300		1G		2009/[64]
GAMESA	G128-4.5 MW	4.5	PMSG	448	690		2G	2-stage planetary	2012/[65]
GENERAL ELECTRIC	GE-4.1-113	4.1	PMSGDD	8–20			–	–	2011/[66]

Table 2
Offshore wind turbine prototypes under development.

Company	Model	Generator data				Gearbox		Status/ref.
		Power (MW)	Tech.	Speed (rpm)	Voltage	Gears	Type	
Sway Turbine AS	ST10	10	PMSGDD		3500			Prototype (2015)/[67]
VESTAS	V164	8	PMSG	–	33–35 kV	1G	–	Prototype/[68]
Northern Power Systems	NPS 8.0-175	8	PMSG	–	33–35 kV	1G	–	Prototype/[77]
Mitsubishi Power Systems Europe	Sea Angel	7	PMSG	–	–	1G–3G	DDT	Prototype (2015)/[69]
GAMESA	G14X-7.0	7						Prototype (2015)/[70]
Bard	Bard 6.5	6.5	PMSG	–	–	–	–	Prototype (2013)/[71]
ALSTOM	HALIADE150	6.3	PMSGDD	11.5	900	–	–	Prototype installed [72]
SIEMENS	SWT-6.0-154	6	PMSGDD	5–11	690	–	–	Prototype (2014–2017)/[73]
Gold Wind	GW 6 MW	6	PMSGDD	11.5		–	–	Prototype (2014)/[74]
Sinovel	SL6000	6	DFIG	–	–	–	Differential gear train and parallel shaft	Prototype/[75]
2-B Energy	2B6	6	–	–	–	–	–	Prototype (2012–2016)/[76]
Yinhe Windpower	GX153-6 MW	6	PMSGDD	11.37	690	–	–	Prototype/[77]
Guodian United Power	UP6000/136	6	DFIG		6600			Protoype (2012-)/[77]
Ming Yang Wind Power	SCD 6 MW	6	PMSG	315		1G	2-stage planetary	Prototype (2013)/[78]
Nordex	N150/6000	6	PMSGDD					Prototype (2014/15)/[79]
AMSC-Hyundai Heavy industries	HQ5500/140	5.5	PMSG			3G		Prototype (2014)/[80]
AMSC-Dongfang Electric	Dongfang 5.5 MW	5.5	–	–	–	–	–	Prototype (2013)/[81]
CSIC-Haizhuang Windpower Equipment	CSIC-Haizuang 5 MW	5	PMSG	–	–	–	–	Prototype (2014)/[82]
Gold Wind	GW 5 MW	5	PMSGDD	–	–	–	–	Prototype (2013)/[77]
Sinovel	SL5000	5	DFIG	–	–	–	Differential gear train and parallel shaft	Prototype/[83]·[79]
Hitachi Ltd (from Fuji Heavy Industries)	Hitachi 5 MW	5	–	–	–	–	–	Prototype (2015)/[77]
XEMC Darwind	XD115	5	PMSGDD	–	3000	–	–	Prototype (2013)/[84]
Mervento		5	PMSGDD	–	–	–	–	Prototype (2013)/[85]
Huayi Electric Company Ltd with Mecal	Huayi 6 MW	6	–	–	–	–	–	Prototype (2013)/[86]
Daewoo Shipbuilding and Marine Engineering	DSME 7.0 MW	7	PMSG	–	–	2G	–	Prototype/[87]
Samsung Heavy industries	S7.0-171	7	PMSG	400	300	1G	Planet flexpin	Prototype/[88]
Shangai Electric	SE 5 MW	5						Prototype (2012)/[77]

Table 3
Offshore wind turbine conceptual designs.

Company/Project	Model	Generator data		Status/year/ref.
		Power (MW)	Technology	
Azimut Project		15	HTSDD	Concept/2020/[89]
GE		15	HTSDD	Concept/-/[66,77]
AMSC	Sea Titan	10	HTSDD	Component prototype/2011/[48]
TECNALIA	SUPRAPOWER	10	HTSDD	Concept/2016/[55]
SUPERPOWER	REACT		HTSDD	Concept/2013/[57]

Nowadays, it is possible to obtain 4 mm-wide HTS 2G tape at a price lower than 35 €/m [11–14] depending on the length required. The maximum price of 4 mm-wide HTS tape to make the HTS generators a potential candidate should be around 15 €/m [12–14]. In order to reduce the HTS tape costs, it is essential to improve the manufacturing technology and increase the volume production [15,16]. Improving the HTS technology and extending industrial sectors to apply HTS technology in the offshore wind energy power systems market are expected for the next decade.

The most experienced HTS generator has been the synchronous generator (HTSSG) due to its easier load torque control and higher efficiency compared with the asynchronous type. Table 4 offers comparison between the generation costs, comparing different conventional technologies to the superconductor technology. Furthermore, Table 5 shows a comparison of total volume, weight and costs as well as overall efficiency of HTSSG.

The subsequent section defines the most common configurations of large HTSSG, followed by a review of the main technological parts and finishing with selected and main relevant projects for offshore wind energy being developed at present.

2.1. Geometric design configurations

Depending on the industrial applications, the nominal characteristics and the performance of the generator there exist different geometric design configurations of these types of electrical machines. Fig. 3 shows a classification of possible selections depending on performance, volume, weight and costs.

The most developed HTS synchronous generator for a range of electrical power from 0.5 to 5 MW and a range of nominal speed from 200 to 4000 rpm has the HTS material in the inductor part: the rotor [18–32]. The AC magnetic field circulating through the fixed armature causes high AC losses in HTS, drastically reducing its critical current. Moreover, a high power cryogenic system is needed to cool down the HTS stator. For these reasons, it is preferable to install HTS wire in the rotor part with a DC magnetic field reducing the HTS AC losses.

Typically, a ferromagnetic yoke is mounted in the outer part of the fixed armature to capture and confine the main circuit flux lines and reduce the total main circuit magnetic reluctance.

In Table 6 the main advantages and disadvantages of using different technological approaches are listed. As shown in Table 6, the air gap armature design allows for working with gap induction fields higher than 1 T [10], which means achieving a higher torque density on the generator shaft. Otherwise a conventional winding is installed, limiting the magnetic induction to lower than 1 T [10], reducing the length required of the HTS racetracks.

Pole saliency could be an alternative to achieve a better magnetic and mechanical behavior of the HTSSG. Fig. 4 shows a typical rough design configuration of a large HTSSG for offshore wind energy applications. This geometric configuration could be modified by different characteristics such as armature design, pole saliency, electromagnetic shields, rotating cryostat design, etc.

2.2. Main technological parts

Electrical generators basically have two main parts: the rotor and the stator. Each part is dealt with separately because of the different technology needed to adapt in the specific case of the HTS electrical generators.

2.2.1. Stator

The armature of the electrical machine has to be designed to obtain the line voltage in its armature windings as well as the required main magnetic field density in the stator yoke and teeth. Depending on the magnetic induction required in the armature winding of the HTS generator an armature is designed with or without ferromagnetic teeth. If magnetic field inductions less than 1 T in the HTS generator air gap are required, it is advisable to install a ferromagnetic teeth armature. In the case where a higher magnetic induction is required, installation of an air gap winding is recommended.

An airgap winding allows the installation of non-magnetic teeth. Although the magnetic reluctance of the main magnetic circuit increases the ferromagnetic power losses decrease. The typical designs of non-ferromagnetic teeth, normally G10 material [33,34], are shown in Fig. 5. An air-gap winding allows more copper per slot to be installed, reducing the radial dimension of the armature conductors and consequently reducing the total radial dimensions of the HTSSG. Otherwise, copper litz conductors must be installed to attenuate eddy current losses due to magnetic dispersion in the air-gap winding part.

Table 4
Comparison of costs between conventional technologies and superconducting technology [17].

	3 MW	6 MW	8 MW	10 MW
PMSGDD ($/MW)	0.3	0.3	0.3	0.3
Geared ($/MW)	0.1	0.1	0.1	0.1
HTSSGDD ($/MW)	0.6	0.4	0.35	0.3

Table 5
Comparison of volume, weight, costs and energy efficiency per MW against HTSSG power.

	3 MW	6 MW	8 MW	10 MW
Specific weight (kg/MW)	24 [17]	17 [17]	16.66 [17]	16 [17]
Specific volume (m^3/MW)	11 [48]	9 [48]	7.5 [48]	6.3 [48]
Specific capital cost ($/MW)	0.6 [17]	0.4 [17]	0.35 [17]	0.3 [17]
Energy efficiency (%)	–	–	–	96 [48]

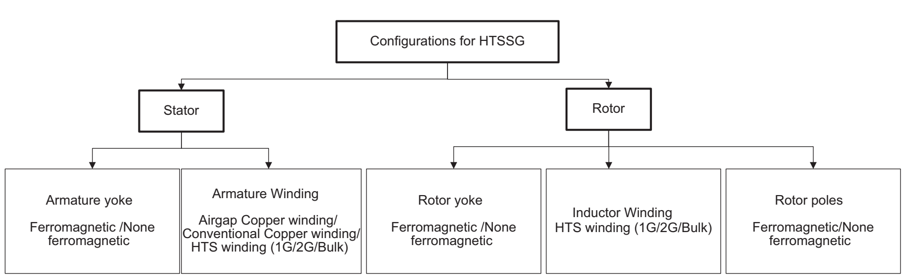

Fig. 3. Different configurations of HTS generators.

Table 6
Advantages/disadvantages of different design characteristics of a HTS generator for wind energy.

Combinations	Advantages		Disadvantages	
	With ferromagnetic material	**Without ferromagnetic material**	**With ferromagnetic material**	**Without ferromagnetic material**
Armature Teeth	– Power density comparable to those of conventional machines – Refrigeration of the winding – Magnetic flux and voltage harmonics – Possible application of retrofit concept [32] – Easily manufactured and proven [32]	– Airgap flux density not limited to saturable effects – Higher power density achieved – Volume and weight reduction – Dielectric insulation capability – No harmonics – Low synchronous reactance – High overload capacity	– Airgap flux densities limited due to saturation effects and ferromagnetic losses	– Install litz wire due to eddy currents [32] – Needs more amps per turn to obtain the same magnetic induction – Extraction of thermal losses [32]
Installing copper litz conductor	– Low ac losses due to eddy currents in copper wire – More mechanical flexibility of conductors		Wire price	
Rotor yoke	– Less HTS material to obtain induction – No frequency losses	– High flux density due to absence of saturation effects – Low rotor mass and inertia [32] – Easy design and construction of cryogenic and structural parts of the rotor [32]		– More HTS is needed to obtain magnetic flux – Torque tube transmission

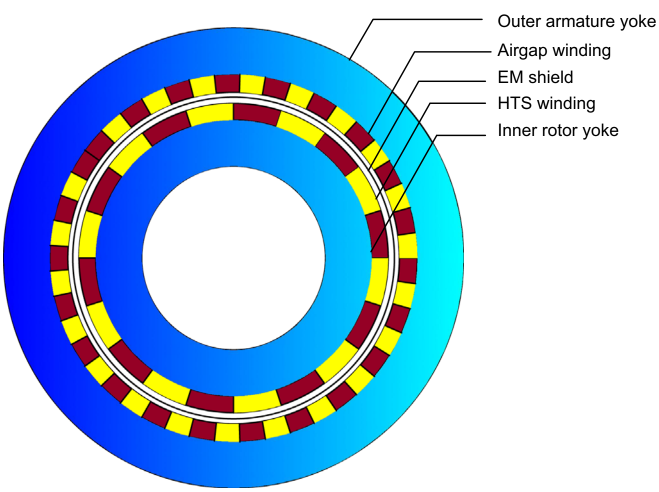

Fig. 4. Typical rough geometric design of large HTSSG for wind energy.

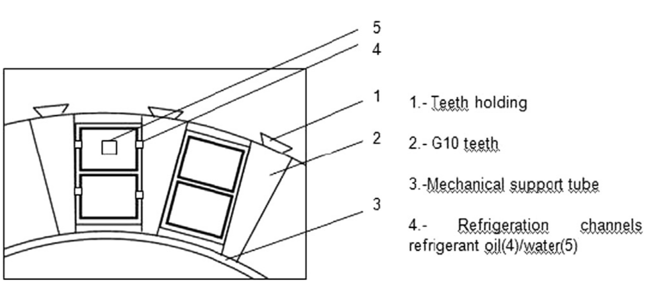

Fig. 5. Details of teeth for an air gap winding.

To confine and capture the magnetic flux of main circuit, and also as a mechanical support, a ferromagnetic yoke is installed in the outer part of the fixed armature. In the inner part of the armature winding (see Fig. 5), a G10 tube [33] is installed to enclose and hold the air-gap winding in the inner part.

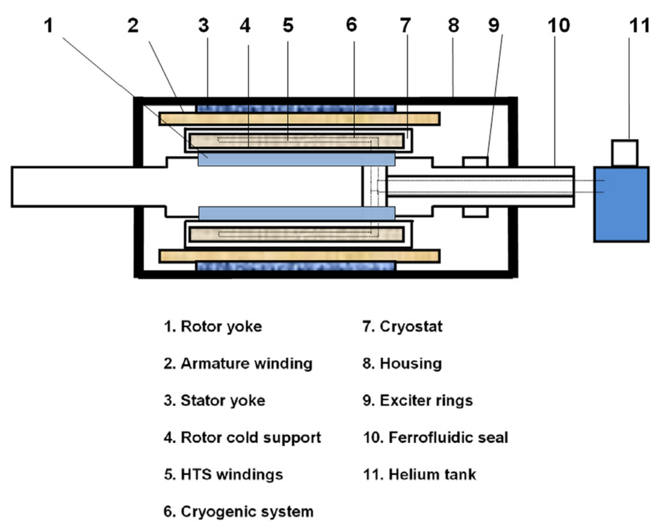

Fig. 6. Warm cryostat of a HTSSG.

2.2.2. Rotor

The rotor has to be designed to induce the operational magnetic field in the main magnetic circuit. For this reason, different HTS rotor technologies are described.

2.2.2.1. Vacuum systems. A HTS rotor needs a vacuum system to minimize thermal conduction and convection from the outer part to the HTS windings. A proper thermal radiation insulation is required in the HTS rotor windings. Furthermore, it is common to use a Multi-Layer Insulation (MLI) covering HTS windings to insulate them from radiation heat load.

There are two main configurations for a cryostat of the HTSSG: the warm cryostat and the cold cryostat.

2.2.2.1.1. Warm cryostat. The cryostat includes only the HTS rotor windings and auxialiary parts but not the structural parts of the rotor or the magnetic rotor parts. Fig. 6 includes a diagram of the warm rotor. As shown, only the HTS windings and the cold

supports are inside the vacuum cryostat despite the magnetic rotor yoke. The helium refrigerant flows from the hollow shaft to the cryostat by a cryogenic transfer system driven by cryogenic pumps. This kind of cryostat permits the installation of conventional ferromagnetic materials such as a yoke. Due to the lower mass to refrigerate inside the cryostat, the cool down is quicker than in cold cryostat. However, a more complex cryostat system is necessary and there is the possibility to use the magnetic rotor yoke as a part of the torque transmission required.

2.2.2.1.2. Cold cryostat. It consists of a cryostat containing the HTS windings, the cold support for them and a magnetic iron yoke as seen in Fig. 7. The magnetic iron yoke has to be specific for these cold temperatures because of the ferromagnetic steel properties. This kind of cryostat and the HTS winding suspension are easier to manufacture. Table 7 presents the main thermal, mechanical and electromagnetic advantages and disadvantages of installing a cold and a warm cryostat.

The vacuum required for these applications oscillates from 10^{-5} to 10^{-6} bar. To achieve this vacuum different pumps are required, the first one a rough vacuum pump to achieve 10^{-2}–10^{-4} bar, and another pump, typically a turbo molecular pump, to achieve the vacuum required. Depending on the time to obtain the vacuum specifications and the total volume of the vacuum chamber, more or fewer vacuum pump units are required.

Other interesting parts of the cryostat are the seals to be installed in order to separate the rotating and the fixed parts. Typically the seals installed in these systems are ferro-fluidic, consisting of a magnetic system around the fixed and the rotating parts controlling the gap tolerance between both parts to achieve the required vacuum.

2.2.2.2. HTS coils. Racetracks are required for obtaining the main magnetic field in the HTSSG. Racetracks are made by HTS wire using different technologies. The first generation HTS wire (1G) is composed of a solder laminated copper stabilizer with a silver alloy matrix with different numbers of HTS $Bi_2Sr_2Ca_2Cu_3O_{10}$ filaments embedded inside. The second generation (2G) is composed of a copper alloy layer, followed by a buffer layer, the HTS material, typically $RE_1Ba_2Cu_3O_7$, where the rare earth used is yttrium (Y), and an outer noble metal layer. Table 8 lists the main geometric, electrical and mechanical characteristics for HTS tapes from AMSC and Superpower Ltd. [35,36].

The percentage reduction of the critical current of HTS tapes depends on the operational temperature and the magnetic field magnitude and direction applied to the tapes, and the mechanical stresses that the tape has been subjected to.

The percentage reduction of critical current from different DC magnetic field directions (perpendicular or parallel to *c* axis) from AMSC and Superpower is presented in Fig. 8. As shown the second generation permits a higher critical current at self-field compared with first generation technology from Innost [37–39].

Fig. 8 reveals the high potential for the electrical parameters of second generation tape to work at high external magnetic field conditions for a temperature of 35 K. As the external magnetic field increases, a lower temperature is needed to maintain a critical current through the HTS tape. The advantageous and disadvantageous characteristics of the HTS 1G and 2G applied to electrical machines are presented in Table 8.

In the fabrication of the coil, the wire is normally wrapped with a few layers of Kapton before the winding process. After the automatic HTS wire winding process, controlling different winding parameters such as strength, winding speed, etc., the coil is impregnated with epoxy components to improve the thermal conductivity and mechanical strength and heated at 60 °C with a rotating movement to solidify the epoxy resin. Due to the

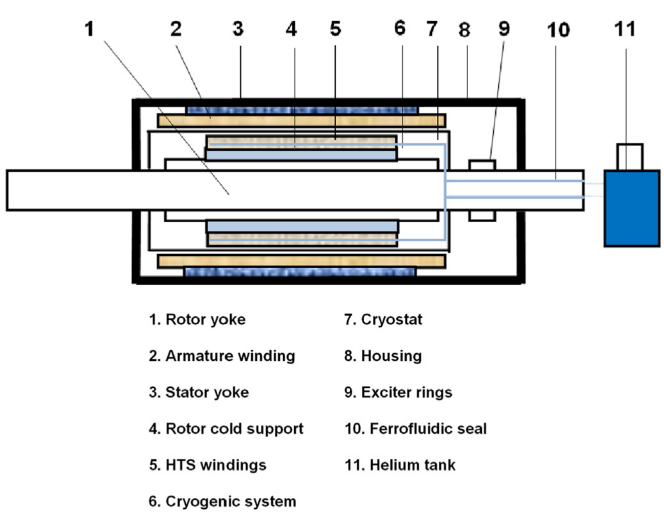

Fig. 7. Cold cryostat of a HTSSG.

Table 8
Geometric, electrical and mechanical properties of HTS tapes commercialized by AMSC and Superpower [35,36].

Specifications	AMSC 1st generation BSCCO wire	AMSC 2nd generation YBCO tape/film (Amperium 4.8)	Superpower 2nd generation YBCO tape/film SCS4050
Width (mm)	4.2–4.4	4.7–4.95	4
Total thickness (mm)	0.255–0.285	0.18–0.22	0.1
Critical bend diameter (mm)	38	15[a]	11
Critical tensile stress (MPa)	200	250	> 550
Critical current at 77 K self-field (A)	145	90–100 (100 m)	80
Maximum rated tensile strain (%)	0.4	0.3[a]	0.45
Maximum rated *c*-axis stress (MPa)		20	

[a] 95% I_c retention.

Table 7
Advantages and disadvantages of a warm and a cold cryostat.

	Advantages	Disadvantages
Cold cryostat	Low magnetic reluctance No additional mechanical transmission [32]	Material mechanical and magnetic properties at cryogenic temperature High thermal inertia [32]
Warm cryostat	Low magnetic reluctance No additional mechanical transmission [32]	High thermal inertia [32] Complex vacuum systems [32]

insulation and epoxy resin impregnation, the mean thickness increases by 1–10% of the total racetrack dimensions [40].

It is necessary to know the quality requirements of the tape before winding, normally given by the manufacturer, and also after winding, to ensure minimum quality parameters of the coil setup given by the tests described as follows.

1. The DC curve characteristic test consists in obtaining the voltage curve on applying DC current at self- or background (parallel or perpendicular to the *ab* plane of HTS tape) field and operational temperature. These tests are critical for the current stability at nominal operation of the HTS generator
2. The AC voltage current characteristic test of racetrack is applying a current ramp for a few seconds at self- or background (parallel or perpendicular to the *ab* plane of the HTS tape) field and operational temperature. EM shields prevent the time and spatial harmonics from the main magnetic field but a reduced part of harmonics can pass through the HTS tapes and could generate current disturbances in the coil.
3. To analyze the transient electrical faults of the racetrack, what is commonly used is a test consisting of a pulse with a trapezoidal fault current profile to investigate the behavior front electrical faults. The cool down temperature for the electrical tests is necessary to control the warm up temperature.
4. It is difficult to predict the responses of HTS wire front variable to AC over-currents. For this reason short duration tests (<1 s) are used in different ranges of critical current ($\times 2$, $\times 3$, $\times 8$), to know the voltage/current behavior.
5. Mechanical properties such as the critical bending radius of the tapes, axial stress and strain (peel test) at different temperatures and self- or background parallel or perpendicular to the *ab* plane magnetic fields are necessary to control the critical current behavior in the presence of mechanical deviations due to the stresses from interactions of its self-field and racetrack current and the winding process.
6. Thermal stability tests consist in finding cooling down and cooling up tests durability to the thermal and mechanical stresses at nominal and over-current conditions.

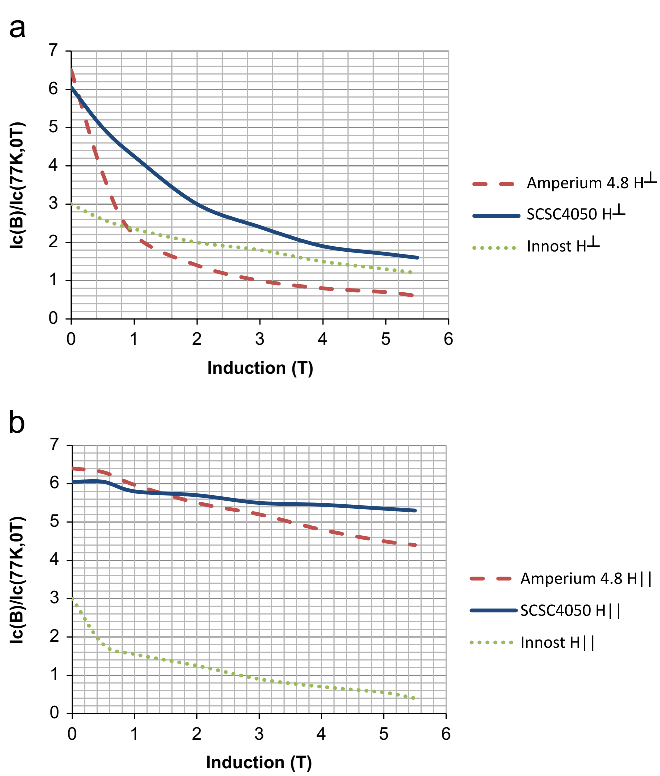

Fig. 8. Normalized critical current a) front magnetic field perpendicular to *c* axis and b) front magnetic field parallel to *c* axis for HTS 1G from Innost [39] and HTS 2G tapes from Superpower [37] and AMSC [38] at 35 K.

The quality of the HTS coil will depend on the results obtained from the tests explained above.

2.2.2.3. Rotor poles and yoke. One of the main characteristics of the rotor poles is the material applied, which could be ferromagnetic or non-ferromagnetic. If non-ferromagnetic rotor poles are installed the magnetic induction of the main circuit is not limited. However, more HTS length is needed to achieve the magnetic field required due to the higher magnetic reluctance of the main circuit and the magnetic dispersion. One of the advantages of installing non-ferromagnetic poles is the low rotor mass obtained and a higher speed cool down that could be achieved. Otherwise, focusing on the mechanical behavior of materials to support the electromagnetic strengths, other more complex systems are needed to support mechanical strengths from HTS windings [32].

If it is decided to install the ferromagnetic rotor poles, HTSSG can operate with a saturation level due to the reduced rotor pole frequency losses because of the rotor's DC magnetic field.

The rotor part should have a cold mechanical support for HTS windings a and a thermal transfer system installed below the HTS windings. Due to the thermal and mechanical effects in cold parts, it is recommended that striations be installed in different critical support zones of the poles and, in case of cold rotor, in the yoke.

2.2.2.4. Electromagnetic shields. The electromagnetic shield consists of a thin tube installed on the external part of the rotor. Usually there are two, one cold, inside the cryostat, and one warm, outside the cryostat. The materials used for shielding are copper or aluminum combined with stainless steel to ensure good mecha-

Table 9
Comparison between Stirling, Gifford–MacMahon cycles and pulse tube refrigerator.

Specifications	Advantages	Disadvantages
Stirling cycle	Low maintenance [32,42] Low vibration Orientation independent High Efficiency	$T > 30$ K [40]
Gifford–McMahon cycle	Robustness Standard cooler for $T < 30$ K[41] 0.5–3 W@4.2 K [44]	High weight Cold head maintenance 100 W@25 K max [43]
Pulse tube refrigerator	Free maintenance (no moving parts) [44]	Low thermal loads 0.5 W@4.2 K [44]

nical behavior front faults. Typically, a thickness of not more than a few millimeters is used in case of two shields.

The electromagnetic shields are used to

1. attenuate space harmonics created by stator coils to HTS windings,
2. attenuate time harmonics created by electronic converters to HTS windings,
3. withstand forces due to short-circuit faults on the stator.

2.2.2.5. Cryogenics systems. The most used cryogenics thermal cycles for HTS motors are the Gifford–McMahon cycle, the Stirling cycle, and the pulse tube. These cycles are made up of an oscillating gas flow and a regenerative heat exchange. The heat extraction depends on the oscillating frequency of the gas flow and the phase angle between pressure and volume during an oscillation period [41]. A pulse tube works in a cyclic compression and expansion into a half open tube without any displacements or movements in the cold part. This would be very attractive to totally reduce the maintenance required for these devices [42]. Table 9 compares the advantages, disadvantages and thermal limits of these three applied cycles.

The most commonly used refrigerator system for HTS generators and motors is the Gifford–MacMahon cycle [22–24] due to its robustness, high industrial applicability and wide range of temperatures to be applied. The most common refrigerant circuits used for HTS generators using two different liquid refrigerants are a closed circuit helium gas circulation system and a phase change neon cooling system.

2.2.2.6. Closed circuit helium gas circulation systems. Helium in gas phase is pumped by a cryopump and circulates from the helium tank directly to the HTS windings. Before the helium arrives at the HTS windings, cold head units are installed to refrigerate the helium gas refrigerant by conduction and extract the heat load from the HTS windings. The operating temperatures of this equipment vary from 5 to 60 K. As mentioned in Section 2.2.2.2, the optimum operation temperature for 1G HTS is from 20 to 30 K whereas for 2G HTS it varies between 40 and 60 K.

A refrigeration circuit for a rotating part is illustrated in Fig. 9. As can be seen, the circuit contains a cryogenic closed refrigeration line pumped by helium pumps and refrigerated by coldheads in the fixed part.

For the coupling of the stationary and rotating part ferro-fluidic seals are used and cold seals are employed to obtain the required vacuum inside the rotor.

For large HTS generators applied to wind energy a similar system has been designed as depicted in Fig. 9 but with the coldheads and helium gas circulation systems installed in the rotating part, taking advantage of the large rotor diameters. This reduces the volume occupied by the cryogenic equipment outside the generator.

2.2.2.7. A phase change neon cooling system. The neon gas system condenses the neon gas at the cryocooler at its boiling temperature of 27.2 K [24]. Liquid neon is then supplied to the rotor and evaporates, removing heat from the rotor in the process, and returns to the cryocooler as a gas. A functional and efficient system can operate as a thermosyphon (no mechanical assistance). Table 10 shows the advantages and disadvantages of the closed circuit helium gas and closed circuit phase change neon cooling system applied to HTSSG.

3. Critical technological parts

Diverse parts of the HTS electrical generator exist that require a specific treatment due to the criticality of their behavior under different operational conditions such as electrical and mechanical faults.

3.1. Mechanical winding stresses

The high flux density obtained inside the main magnetic circuit of the HTS generator combined with the armature current generates a huge mechanical force in each HTS winding. This means it is highly important to properly set the HTS windings and mechanically support them so as to not deform them and ensure the highest critical current in HTS windings. Otherwise it may reduce the electrical properties of HTS and in the worst case, quenching the HTS windings. It is well known that the mechanical forces in the generator radial direction are higher than in the tangential direction which means it is necessary to reinforce this part [46]. For this reason, installation of pole saliency or radial supports are required, to hold the HTSSG correctly in the radial direction.

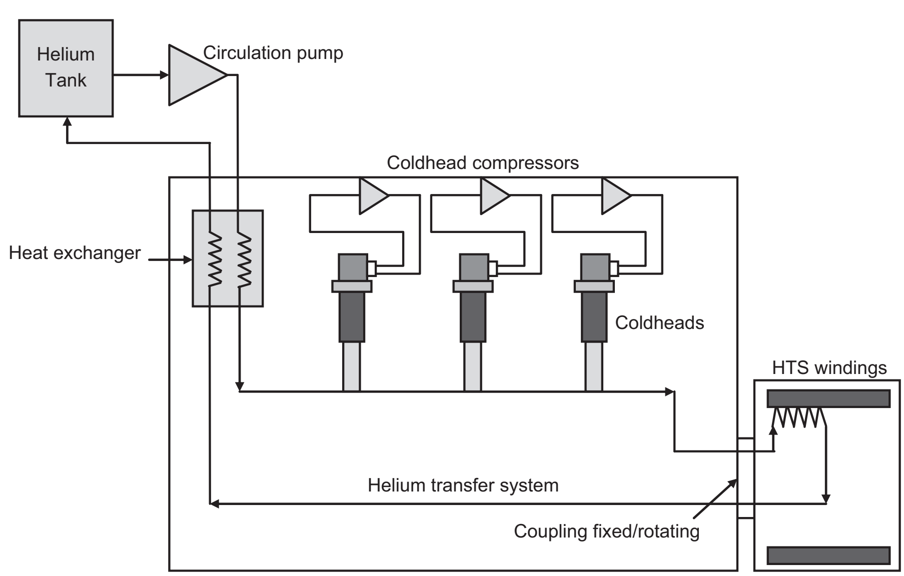

Fig. 9. Cryogenic equipment and system for HTSSG.

Table 10
Advantages and disadvantages of the main refrigeration systems of a rotor.

Specifications	Advantages	Disadvantages
Closed circuit 1 phase helium gas cooling systems	Wide temperature ranges Experienced and standard technical solution	
Two phases change neon cooling systems	Easy mechanical decoupling between the fixed and rotating part High efficiency using latent heat [45]	Cold head temperature varies with heat load (needing a heater) [45] Coolant temperature fixed at 27 K (HTS operating temperature could be higher) Cooling will be non-uniform (coil stresses) Requires conduction thermal paths [45]

3.2. Torque transmission

A large HTS generator for wind energy will have a high rated torque that has to be transmitted from HTS coils to the generator shaft with a high thermal gradient. There are a few options proposed by different companies to solve this problem. The first option involves a mechanical torsion transmission with carbon fiber torsion rods designed to reduce thermal conduction losses between HTS windings and the iron yoke [10]. The second option is to install a torque tube connected with cold HTS winding support using non-thermal conductive materials. The mechanical transmission in the second case could be smoother than the first case but the thermal transmission would most likely be worse [33].

3.3. Temperature effects

The cool-up and -down for a large HTSSG will be a critical aspect due to the thermal strain and consequently stress as a result of a high thermal gradient. There exist different methods to reduce the stresses produced in the cold parts. One of the most useful and easier ones is to adapt striations in the cold parts to have the available free space to deform freely, without stresses. Depending on the cold part's shape, different kinds of striations or holes are installed in the cold material. Another method entails embedding the cold part with a material with a negative thermal coefficient to support the positive thermal coefficient of the cold weight.

4. Selected R&D projects

There exist a huge number of projects related to electrical generators using HTS. The most relevant projects and designs of HTS generators specifically for offshore wind power systems are presented here. The projects described below have been followed up by some of the most prestigious electrical companies in the world.

4.1. Direct Drive HTS wind turbine generation (Converteam)

The Direct Drive wind turbine HTS generator developed by Converteam started in 2004 and was partly supported by a grant of UK Department of Trade and Industry [18]. It consists of three differentiated phases; the first phase, a conceptual design of the full size generator, the second, a detailed design with a cost model performance and the third a prototype of 200 kNm.

Initially, the HTS generator specification was 8 MW, 12 rpm for an offshore wind turbine application, obtaining a shaft torque of 6.5 MNm and a rotor blade diameter of 160 m. The design has an electrical generator rotor diameter of 5 m with an overall length of 2.2 m and a mass of 100 metric tons ™ [18,47].

The geometric configuration is made up of an air gap winding and HTS rotor with non-magnetic pole bodies; but what has been seen studied too has an air gap winding with magnetic pole bodies due to the possibility of increasing the magnetic field of the rotor poles because at DC conditions the magnetic induction can operate highly saturated without losses [18].

A two-dimensional non-linear time stepping electromagnetic finite element simulation is done using Vector Field Opera Software. An electrical power of 10 MW is reached with electromagnetic torque of 6 MNm for a speed of 8 rpm with the required dimensions. Rotor losses due to the rotor shield and coil support losses are in the range of 10 W so they are insignificant compared with stator armature losses, 55 kW [10]. Otherwise, it is considered feasible to reduce armature losses lower than 6 kW.

A cryogenic equipment with helium gas as a liquid refrigerant operating at 30 K is chosen [18,47]. In 2008 the design of the major components was completed and the manufacturing process of a prototype was finished in 2010 [18].

Table 11
Main specifications for Sea Titan [25,26,48–50].

Parameters	Value	Units
MVA rating	10,400	kV A
Output rated load	10,000	kW
Power factor	> 0.95	PU
Nominal speed	10	rpm
Line voltage	690	V
Synch. reactance	0.3–0.4	PU
Weight	150	Tm
Efficiency at rated load	96	%
Field adjustment	Yes	

4.2. Sea Titan 10 MW 10 rpm (AMSC)

AMSC's Windtec, an AMSC subsidiary located in Klagenfurt, Austria, has completed a design of a 10 MW 10 rpm HTS generator for wind energy applications [25,26,48–50]. The project started in 2008 after a comparative study realized by the National Renewable Energy Laboratory (NREL) and American Superconductor to perform a comparative study between conventional direct drive technologies applied to wind energy, surface permanent magnet generators, and against high temperature superconductor generators for wind energy [17].

The generator model designed has an outer diameter range of 4.5–5 m and a length range of 2–3 m, with a total mass from 150 to 180 Tm. Table 11 summarizes the main specifications of the Sea Titan [48,25,26].

The NIST Advanced Technology Program (ATP) sponsored the development of the pole sets with HTS 2G technology scaled for this application, the cryogenic equipment and system required and the stator technology (the latter with TECO-Westinghouse as a joint venture partner of AMSC) [26].

The pole set was 1270 mm by 535 mm using 12 mm-wide tape and 1500 m of HTS 2G wire. With this pole set the thermal mechanical and electrical model used was validated [25,26].

The design and construction of a scale cryogenic system was successful. A cryogenic system was designed to apply the

coldheads in the rotor part and the quantity and placements of the Gifford–McMahon cryocoolers and the centrifugal fans to be applied in the rotating part were obtained [25,26].

There was a significant study of the components reliability, done by the ATP, using a mean time before failure system (MTBF), which revealed that the HTS rotor of Sea Titan with its HTS and cryogenic and vacuum system will have a lifetime of over 30 years without maintenance. The rotor stress occurs when it is thermally cycled; this reliability plan allocates a thermal cycle per year for which there is no need in practice [25,26].

4.3. 8 MW HTSSG (Technova Inc., N. Maki)

This work was supported by Technova Inc., developed by N. Maki, started in 2004 and finished in 2008 [51–53]. It consists of a method to design large HTS generators for wind power systems. An analysis of different wind HTSSG based on different variables of interest for electrical machines design as pole number, outer diameter and synchronous reactance had been done. This work focused on a range of power from 2 to 8 MW and a range of speed 21.5–12 rpm [52]. The analysis reveals that increasing the number of poles, the HTS length needed and the total weight of the generator are reduced but not the HTSSG overall efficiency [52]. Moreover, the tendency of increasing the generator weight as the synchronous reactance of the generator increases is explained.

The possibilities considered for the study of a HTS generator of 8 MW and 12 rpm are

1. HTS electrical machines with non-ferromagnetic rotor poles and with and air gap winding [52],
2. HTS electrical machines with magnetic poles (Ni alloy) and a conventional stator [52],
3. HTS electrical machines with conventional rotor and stator [52].

The total generator weight of these configurations is about 200 Tm, but the length of HTS needed is highly reduced (80% approximately) in the third configuration [52].

The analysis concludes that the best selection was a conventional stator with ferromagnetic rotor poles operated at magnetically saturated conditions [51–53].

5. Discussion

At present, the concept project of HTSSG for offshore wind turbines developed at this time reveals that HTSSG can operate at a higher torque and power density, consequently requiring lower dimensions compared with conventional technologies such as PMSGDD. As a result of the lower electrical machine dimensions and the materials used for a HTSSG, a lower overall weight is achieved, mainly due to a reduction of structural materials to radially support the HTSSG rotor [54]. As a simple example, a 4.5–5 m diameter is obtained for 10 MW–10 rpm with a total weight of 160 Tm whereas with conventional technology, a 10 m diameter with a total weight of 260–320 Tm is required [55,48].

Currently, the price for offshore wind power is 1.5 M€/MW [56]. The current commercial price for 12 mm-wide HTS tape is from 55 to 85 €/m depending on the total length provided [57;58]. What is expected for a 5 MW HTSSG Direct Drive using a 12 mm-wide HTS tape is an overall length from 50 to 100 km [56], reaching a total cost of 2.75 M€ just for the HTS material, whereas the total conventional offshore wind power for 5 MW is 7.5 M€.

The wire length required for a HTSSG depends on the specifications of magnetic field to be achieved. Depending on this magnetic field, the airgap generator diameter and then the total volume of the HTSSG could be reduced. The range of the airgap magnetic field for HTSSG tends to be from 1 to 4 T [55,59] depending on the HTS tape in the fabrication process as well as the commercial manufacturer. The maximum air gap magnetic field limit is due to the reduction of HTS tapes critical current due to the self-magnetic field across it. For this reason, it will be reasonable to design HTSSG optimizing the total generator cost function on these parameters.

The future trends and prospects for HTS tapes and cables indicate a high reduction for the next decade – more than 80% in some cases [12–14] – due to the different critical points such as the higher volume request as well as the improvement in HTS tape, cable fabrication methods and the HTS tape effective transversal section. In the next five years there will be a few ongoing projects with demonstrators planned to clarify the most relevant technical points [55,57] such as the improvements in HTS wires, reliability, vacuum and cryogenic systems as well as mechanical behavior for rotating parts.

6. Conclusions

The HTS are a potential candidate to develop the electrical power conversion systems with wind power development specifically for the offshore industry. On the other hand, the HTSSG, particularly the rotor electrical generator technology, requires more research investment specifically in demonstrators and prototype fabrication to determine and clear up electromagnetic, thermal and mechanical technological aspects as well as in a long term, efficiency and maintenance requirements to make the entrance of the HTSSG technology successful.

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